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Original Paper
J. Glob. Innov. Agric. Sci., 2026, 14(2):627-639
ISSN (Online): 2788-4546; ISSN (Print):2788-4538
DOI: https://doi.org/10.22194/JGIAS/26.1728
http://www.jgiass.com

Society for Innovative Agriculture

Improvement of Tomato Tolerance to Water Stress through the Application of Potassium Phosphate (KH_2PO_4)

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The aim of the present study was to demonstrate the ameliorative effect of potassium phosphate on water stress tolerance in the BRNADINE 5656 variety of tomato (*Solanum lycopersicum* L.). The nine treatments studied were made by mixing two levels of potassium phosphate (0.5 g/L and 1 g/L) with three different irrigation schedules based on field size: 100%, 75% and 50%. The experiment was conducted under natural conditions in an intelligent agro-photovoltaic greenhouse in pots containing 2.5 kg of a mixture of soil (70%) and peat (30%). The measurements performed related to growth parameters (aerial and root biomass, stem and root length, number of leaves and fruits), water content and biochemical parameters (proline, soluble sugars, chlorophyll (a), (b) and carotenoids content). The results obtained showed that water stress reduced all measured parameters, confirming the sensitivity of tomato. The reductions varied according to the severity of stress (-7% to -56%). Under water stress, the addition of KH_2PO_4 only had a beneficial effect on root dry mass, and on the water content of the aerial part, chlorophyll pigments, and carotenoids. In the presence of 1 g/L of KH_2PO_4, the water content of the aerial part increased from 1.86 to 2.63 mL·g^{-1} DW and from 1.77 to 3.57 mL·g^{-1} DW under moderate and severe water deficit, respectively, compared to the control of each stressed treatment. For the same treatment, root biomass increased from 5.84 to 11.43 g DW and from 5.46 to 7.85 g DW under moderate and severe water deficit, respectively. Similarly, the contents of chlorophyll (a), (b), and carotenoids increased by 40.92% and 20.66%, 62.34% and 39.93%, and 59.6% and 36.14% under moderate and severe stress, respectively.

Keywords: *Solanum lycopersicum* L., abiotic stress, drought stress, agronomic parameters, water potential, stomatal conductance

INTRODUCTION

Tomato growing occupies a very important place in Morocco's socio-economic context. Production is constantly increasing to meet local and export market demand. Its popularity as a staple food can be explained by its balanced nutritional value and affordable price. However, its cultivation remains hypothecated by biotic and abiotic constraints, mainly in arid and semi-arid regions. In this respect, rising temperatures, irregular rainfall and prolonged periods of drought have reduced the yield of all crops combined (Shahzad et al., 2024; Asati et al., 2022; Habib et al., 2022). Indeed, the negative effects of drought can manifest themselves at any vegetative stage (Keerthi Sree et al., 2023), reducing all parameters: germination rate, growth, development and yield (Araus et al., 2002; Bradford and Hsiao, 1982; Walker & Hsiao 1992). However, the intensity of its depressive effect depends on the duration of application and the vegetative stage of the crop (Bradford & Hsiao, 1982). These reductions are essentially attributed to alterations and/or disruption of several biochemical and physiological functions vital to the plant (Jaleel et al., 2009). Water is vital for plants as it serves as the reaction medium for all enzymatic processes, while also influencing the organization, morphology, and elongation of plant organs. Moreover, it functions as the plant's circulatory system, ensuring efficient absorption of soil minerals and their distribution to all plant organs. However, prolonged water stress triggers a series of

Moussa, W., Boughribil, S., Amenzou, N. & Benahmed, A. (2026). Improvement of tomato tolerance to water stress through the application of potassium phosphate (KH_2PO_4). *Journal of Global Innovations in Agricultural Sciences, 14*, (2)627-639.
[Received 17 Jan 2025; Accepted 5 Jul 2025; Published 11 Jan 2026]

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morphological and physiological changes in many plant species, leading to reduced yield (Levigneron et al., 1995). Under water stress, plants reduce the opening of their stomata to minimize gas exchange with their atmosphere (Jaleel et al., 2009). This first adaptive strategy implemented by the stressed plant disrupts the absorption of water and mineral salts by the roots (Kaushal and Wani, 2016). Under these stressful conditions, the water potential and turgidity of leaf cells record decreases (Aslam et al., 2014). As a result, these cellular dehydrations inhibit expansion and cell division, reducing leaf area, stem elongation and root proliferation (Taiz et al., 2015; Farooq et al., 2009; Chaves et al., 2009). The world's growing food deficit calls for solutions to improve crop production to meet the needs of an ever-increasing population. One of the approaches currently used is to identify resistant species or varieties that are capable of developing in the presence of water stress. However, it would be interesting to act on the mineral composition in the rhizospheres of sensitive plants to improve their tolerance to water stress. To this end, research has shown that the application of potassium fertilizer improved the growth of barley and sunflower (Lindhauer, 1985), and maize (Aslam et al., 2014) grown under water stress. This ameliorative effect is attributed to the simultaneous involvement of water and potassium in the unfolding of several physiological activities such as photosynthesis, cell growth and stomatal conductance (Hsiao et al., 1976). In the same vein, (Lindhauer, 1985) showed that the application of potassium at doses higher than its agronomic optimum improved dry matter production and photosynthetic surface expansion by ensuring better water availability. Battie-Laclau et al. (2013) also reported positive effects on photosynthetic organs, not only stimulating new leaf formation but also delaying leaf senescence. Excess potassium in the soil solution appears to optimize water use efficiency (Grzebisz et al., 2013), improving uptake by the stressed plant's root system and regulating transpiration via the stomata (Arquero et al., 2006).

Potassium phosphate (KH_2PO_4) plays a crucial role in enhancing plant tolerance to water stress by acting on multiple physiological and biochemical levels (Lester et al., 2005). Potassium (K^+), an essential cation in its free form in living plant organisms (Sardans et al., 2021), is involved in the regulation of ionic homeostasis by maintaining osmotic and electrolyte balance in plant cells. Under water stress, plants close their stomata to reduce transpiration (Hsiao et al., 1976; Nakro et al., 2020). This process requires precise regulation of K^+ ion fluxes to adjust the osmotic potential of cells (Zhang et al., 2016; Zhu et al., 2016). Therefore, potassium phosphate provides K^+, which helps maintain cell turgor and stabilize cellular membranes, which is crucial for plant survival under stressful conditions. It also improves photosynthetic efficiency by activating enzymes involved in the Calvin cycle, such as ribulose-1, 5-bisphosphate carboxylase/ oxygenase (RuBisCO) (Sardans et al., 2021), to produce the energy needed for survival under water-deficit conditions. Under water stress, plants accumulate compatible osmotic solutes (such as proline, soluble sugars, and glycine betaine) to lower their osmotic potential and maintain water uptake. In this regard, potassium promotes the synthesis of osmoprotectants by activating specific enzymes and participating in the regulation of associated metabolic pathways (Cuin et al., 2018; Zain et al., 2014; Teixeira et al., 2007; Wang et al., 2010).

Naturally, water stress induces excessive production of reactive oxygen species (ROS), which can damage membrane lipids, proteins, and DNA. However, potassium enhances the activity of antioxidant enzyme systems such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), thereby helping to neutralize ROS and protect cells from oxidative damage (Gill & Tuteja, 2010; Bhattacharjee, 2012). It also contributes to the structural stability of cell membranes by interacting with phospholipids and modulating their fluidity. This stabilization prevents ion leakage and preserves cellular integrity under water stress conditions (Cakmak et al., 2005).

It improves water use efficiency (WUE) by directly influencing the opening and closing of stomata through K^+ ion fluxes in guard cells (Zhang et al., 2016; Zhu et al., 2016). Thus, it allows plants to maximize their water use efficiency while minimizing water loss through transpiration (Wang et al., 2013). Potassium acts as a cofactor for many enzymes involved in energy metabolism, such as ATPase and enzymes of the Krebs cycle, ensuring better energy availability for defense mechanisms against water stress (Marschner, 2012). Finally, it plays a central role in cellular signaling cascades, particularly in response to hormonal signals such as abscisic acid (ABA), which is involved in the water stress response. It facilitates rapid signal transmission between cells, enabling a coordinated and effective response to stress (Aubert, 2011; Rai & Takabe, 2006). These combined mechanisms allow plants to better withstand periods of drought and maintain their growth and productivity even in unfavorable environments. Currently, the transcriptional and post-transcriptional regulation of passive and active membrane K^+ transporters is a key area of research due to their important role in plant development, function, and regulation of responses to environmental stresses (Anschütz et al., 2014; Shahzad et al., 2016; Dreyer et al., 2016).

The present work, part of this approach, aims to determine the optimal concentration of potassium phosphate KH_2PO_4 to improve the tolerance of tomato plants grown under water stress.

MATERIALS AND METHODS

***Plant material*:** The tomato (*Solanum lycopersicum*) variety used in this experiment is BRNADINE 5656. It is an F1 hybrid with indeterminate growth, developed by Hi-Tech

Seeds MAROC. This variety is widely cultivated both in greenhouses and in open fields and is adaptable to all soil types. It was selected for its fruit quality, good response to mineral fertilization (nitrogen, potassium, phosphorus), and especially for its high sensitivity to abiotic stresses, particularly water and salinity stress, making it an excellent model for our study.

***Soil used*:** The growing medium used is an agricultural soil from the Rabat-Salé-Morocco region. Its texture is clay-loam-sandy (40.8%, 34.8% and 24.4%). Chemical analysis of the soil was carried out using the X-ray Fluorescence method at the laboratory of the Centre National de l'Énergie, des Sciences et des Techniques Nucléaires (CNESTEN). The concentrations of the various elements analyzed are recorded in Table 1.

Table 1. Mineral composition of the soil used.

(mg/kg)	Concentration	Uncertainty
Mn	356	46
Cr	51,0	46,0
Ni	13,5	6,0
Cu	9,5	4,5
Zn	30,5	5,0
Rb	12,5	3,0
Sr	20,5	4,0
Zr	82,0	9,0
Ba	86,0	70,5
Pb	11,5	10,0

***Conducting the trial*:** The cultivation was carried out in a smart agro-photovoltaic greenhouse installed at the Nuclear Studies Center in Maamoura, over a period from February 22 to June 11, 2024 (110 days).

This prototype station was built as part of a CR-SEAPI project funded by IRESEN, under natural lighting. Seeds of the tomato variety studied were disinfected with 10% sodium hypochlorite for 10 min, then washed several times with distilled water to remove traces of sodium hypochlorite. The disinfected seeds were sown in trays filled with peat moss (Kekkilä brand), to a depth of 1 cm. Germination of the seeds took place under controlled conditions, with the temperature maintained at 26°C and a constantly humid environment, thanks to regular watering to prevent root rot. After five days, the germinated seedlings were transplanted into holes dug in pots containing 2.5 Kg of a mixture of soil (70%) and peat (30%), at the same depth as the honeycomb trays.

Water stress was applied in pots using the gravimetric method (Keerthi Sree et al., 2023). Before starting the experiment, the pots were saturated with water and then drained for 24 hours to reach field capacity. This served as a reference point for defining the water stress levels to be studied. The three treatments were applied by adjusting the substrate's water content to a specific percentage of the field capacity in each pot: 100%, 75%, and 50%. The volume applied at each irrigation for the 75% and 50% treatments was calculated based on that of the control (100%). The control volume was determined by irrigating until a slight drainage occurred.

For each irrigation regime, three concentrations of potassium phosphate (KH_2PO_4) were applied: 0 g/L, 0.5 g/L, and 1 g/L. The volume of potassium phosphate solution was applied twice weekly, in addition to that determined for each irrigation, throughout the plant growing cycle. Table 2 shows the nine treatments studied.

Table 2. Mineral composition of the soil sed.

Treatment	Irrigation Level (%)	KH_2PO_4 Concentration (g/L)
T1	100 %	0
T2	100 %	0,5
T3	100 %	1
T4	75 %	0
T5	75 %	0,5
T6	75 %	1
T7	50 %	0
T8	50 %	0,5
T9	50 %	1

***Methods of Analysis*:** At the fruit stage, which corresponds to 16 weeks of cultivation, various agronomic and biochemical parameters were measured to assess the impact of treatments on the growth and development of tomato plants.

***Agronomic parameters*:** The agronomic parameters assessed in this study enable us to characterize the growth and development of tomato plants under different treatments. Biomass was estimated by measuring the fresh and dry mass of the various organs, before and after drying at 70°C for 48 hours. The water content of the organs was determined by relating the difference between fresh and dry mass to the latter, expressed in mL. g^{-1} DM. According to the literature, this parameter will allow us to deduce that water absorption and dry biomass production are only maintained if the plant has been able to perform osmoregulation, through ions and/or osmolytes, at the cellular level. At the same time, morphological measurements were taken, including the number of leaves per plant, the length of the aerial part and the root length. A biomass distribution indicator, the ratio of root dry mass to total plant dry mass (R/PA), was also calculated to assess resource allocation between above- and below-ground parts. Finally, productivity was estimated by counting the total number of fruits per plant, thus providing an indication of the impact of applied treatments on yield.

***Biochemical parameters*:** Proline and sugar contents (total sugars and soluble sugars expressed as glucose content) were determined using the methods of Monneveux & Nemmar (1986) and Dubois et al. (1956) respectively. On the other hand, chlorophyll (a), chlorophyll (b) and carotenoid contents were calculated using the method of Dubois et al. (1956)

***Statistical analysis*:** Statistical analysis was performed using IBM SPSS software. The results were subjected to a one-way analysis of variance (ANOVA), and the means, based on three (3) replicates per treatment, were compared using Tukey's test at a 5% significance level.

RESULTS

Presentation of agronomic analysis results

***Fresh and dry weight of the Aerial part and root part*:** The application of water stress resulted in a reduction in the mass of the plant's fresh aerial matter (Fig. 1). Expressing the results as % of the control shows that the reduction in the mass of these organs tends to decrease with the extent of water stress, which is -37.37% in the presence of moderate stress (75% at field capacity) and -56.01% with severe stress (50% at field capacity). The addition of KH_2PO_4 to the growing medium improved plant fresh matter production in all treatments, in proportion to the concentration added to the irrigation solution (Fig. 1). Under water stress, the highest values of fresh mass were recorded in the presence of 1g / L KH_2PO_4. With the latter dose and compared with the control for each treatment, this increase in aerial mass was +52.5%, +49.52% and +44.07% respectively in control, moderately stressed and severely stressed plants. The application of water stress to the plants resulted in a reduction in dry matter mass of -24.18% only in the severely stressed plants, with no apparent effect in the moderately stressed plants (Fig. 1). The addition of KH_2PO_4 to the irrigation solution resulted in an increase in dry matter, only in unstressed plants, of +57.17% and +61.98% respectively in the presence of 0.5 g / L and 1 g /L. On the other hand, in the presence of water stress, the values decreased regardless of the concentration applied (Fig.1). This result clearly shows that the increase in fresh weight of aerial organs stressed in the presence of KH_2PO_4 is essentially attributed to their hydric hydration and not to an increase in their number and/or mass.

For roots, the application of water stress leads to a reduction in both fresh and dry weight, with a more marked effect on the latter. Root dry matter mass decreases by -15% and -20.6% respectively under an irrigation regime of 75% and 50% at field capacity (Fig. 2). However, enrichment of the irrigation solution with KH_2PO_4 improved root fresh weight only in control and moderately stressed plants, with no discernible effect under severe stress. On the other hand, dry weight increased in proportion to the 1g/L concentration of KH_2PO_4 applied, whatever the treatment studied, with the highest values recorded in unstressed plants. Compared with the control of each treatment, the increases are 76.5%, 95.6% and 53.5% respectively in the presence of normal, moderate and severe irrigation regimes (Fig. 2).

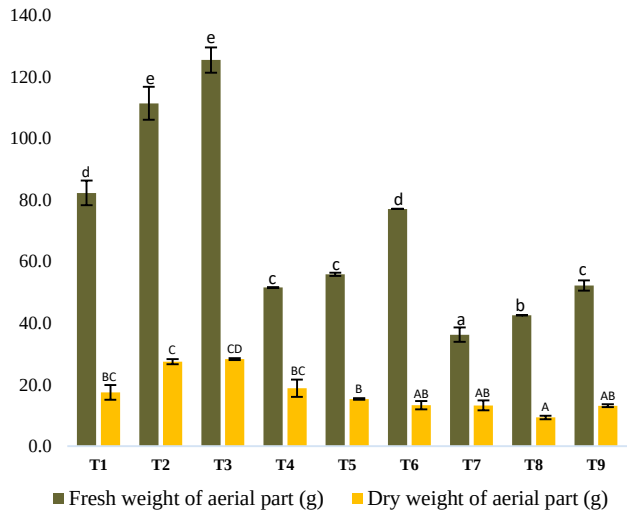

Figure 1. Effect of potassium phosphate (KH_2PO_4) on the fresh and dry weights of the above-ground part (in g) of tomato grown under three irrigation regimes. 95% confidence interval for the mean of 3 replicates. Means followed by different letters are significantly different ($p < 0.05$).

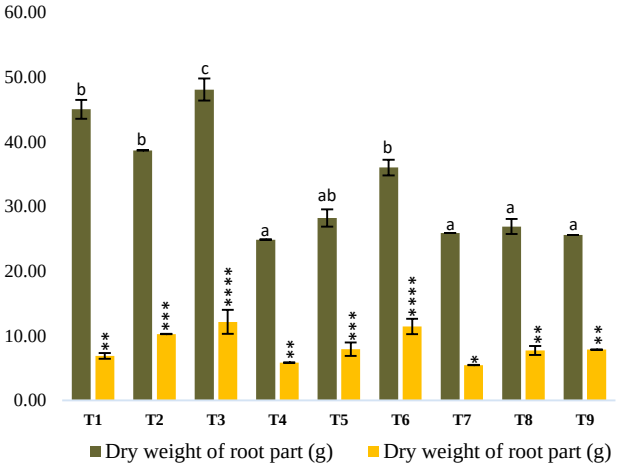

Figure 2. Effect of potassium phosphate (KH_2PO_4) on fresh and dry root weights (in g) of tomato grown under three irrigation regimes. 95% confidence interval for the mean of 3 replicates. Means followed by different letters are significantly different ($p < 0.05$). Means with the same number of stars (*) are not significantly different according to Tukey's test ($p < 0.05$).

Comparing the behavior of the two parts of the plant, the results show that the addition of KH_2PO_4 improved root growth to increase the absorption surface area by prospecting

a large volume of substrate, even in the presence of severe water stress. Therefore, an exogenous supply of KH_2PO_4 is essential to maintain root apical meristem cell multiplication in plants grown under even severe water stress.

***Fresh weight and dry weight of fruit*:** Under an irrigation regime of 100% at field capacity, the decreases in fruit fresh weight recorded were inversely proportional to the concentration of KH_2PO_4 added to the medium. On the other hand, in the presence of water stress, the addition of KH_2PO_4 to the irrigation solution improved the hydration of these fruits, with a more marked effect in plants subjected to moderate stress (75% to field capacity). In the latter case, the increase in fresh weight was proportional to the concentration of KH_2PO_4. But for the dry weight of the same organs, the improving effect is only perceptible in the presence of the moderate stress (75% at field capacity) (Fig. 3). This result shows that an exogenous supply of KH_2PO_4 to plants grown under moderate water stress (75% at field capacity), stimulated the production of plant matter by ensuring turgidity necessary for cell multiplication in all parts of the fruit.

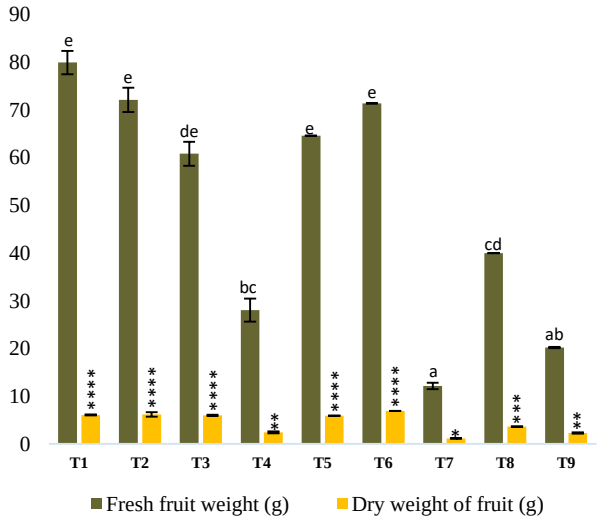

Figure 3. Effect of potassium phosphate (KH_2PO_4) on fresh and dry fruit weights (in g), tomato grown under three irrigation regimes. 95% confidence interval for the mean of 3 replicates. Means followed by different letters are significantly different ($p < 0.05$). Means with the same number of stars (*) are not significantly different according to Tukey's test ($p < 0.05$).

***Water content of each organ according to the applied treatments*:** Results relating to water content clearly show that fruits are the most hydrated organs and that their water supply tends to decrease both in the presence of water stress and with the application of KH_2PO_4 in all treatments combined. Thus, the mechanisms involved in directing water flow to fruit are less sensitive to water stress than those involved in the growth and development of other plant organs. Hydration of aerial organs decreases as a function of the concentration of KH_2PO_4 added to the irrigation solution in unstressed plants, which is -43.2% and only -16.1% respectively at moderate and severe stress. But compared with the control of each stressed treatment, water contents of aerial organs showed increases, which are variable according to the added concentration of KH_2PO_4. Under moderate water stress, aerial organ hydration was improved by + 41.4% and + 163.4% respectively with 0.5 g/L and 1 g/L KH_2PO_4. In the case of severe stress, water supply to these aerial organs was improved by + 101.7% and + 68.4% with the low and high dose of KH_2PO_4 respectively (Fig. 4).

In conclusion, the hydration of the aerial organs increased, according to the concentration of KH_2PO_4 added to the irrigation solution in stressed plants. But the best hydration was obtained with the addition of 1 g of KH_2PO_4 under moderate water stress.

For the roots, the fluctuations recorded were similar to those of the aerial organs (Fig. 4).

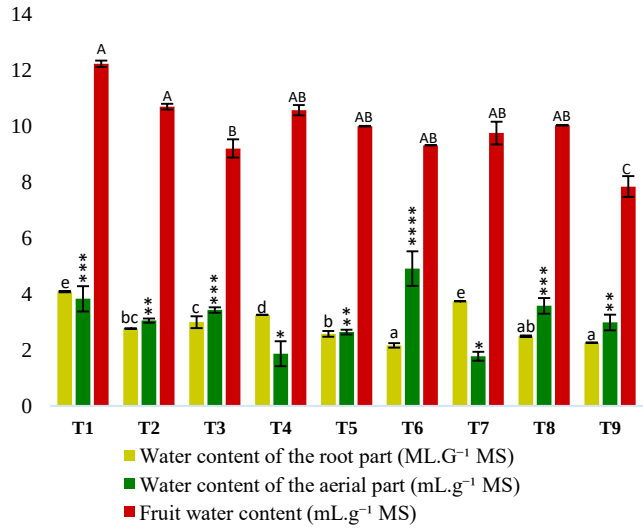

Figure 4. Effect of potassium phosphate (KH_2PO_4) on the water content (mL.g-1 MS) of each organ as a function of treatments applied to tomatoes grown under three irrigation regimes. 95% confidence interval for the average of 3 repetitions. The averages followed by different letters are significantly different ($p < 0.05$). The averages with the same number of stars (*) do not differ significantly between them according to the Tukey test ($p < 0.05$).

***The root-to-total plant dry mass ratio (R/PA)*:** The R/PA ratio tends to increase with the concentration of KH_2PO_4,

indicating that root growth is favored compared to that of the aerial part. This effect is particularly pronounced in plants grown under moderate water stress (75%), where the highest value is recorded with 1 g/L of KH_2PO_4. Under severe stress (50%), although the increase is less marked, the R/PA ratio remains higher than that of the control, suggesting that KH_2PO_4 contributes to maintaining root development even in a situation of pronounced water deficit (Fig. 5).

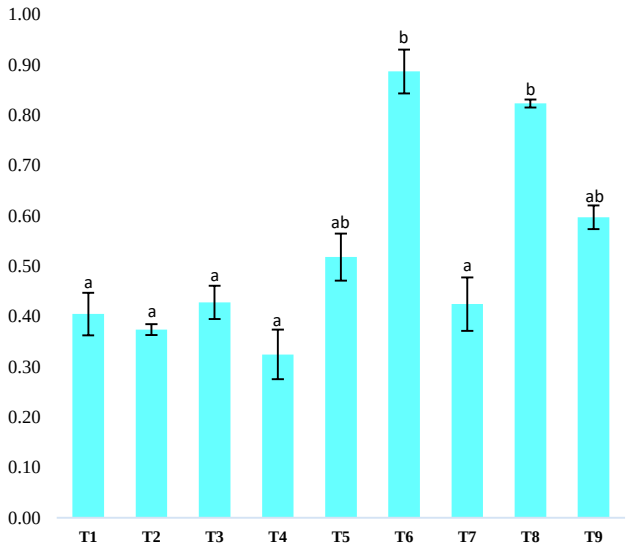

Figure 5. Effect of potassium phosphate (KH_2PO_4) on the ratio of dry root mass to dry whole plant mass (R/PA) in tomatoes grown under three irrigation regimes. 95% confidence interval for the average of 3 repetitions. The averages followed by different letters are significantly different ($p < 0.05$).

***Number of leaves*:** Water stress reduces the number of leaves by - 7.69% and - 15.38% respectively at moderate and severe application compared to control. However, this number increases with the concentration of KH_2PO_4 added in the plant culture medium from all treatments studied (Fig. 6). This effect is higher as the concentration of KH_2PO_4 in the medium increases, indicating a more pronounced effect on leaf neoformation.

***Yield*:** The number of fruits per plant decreases with increasing water stress (Fig. 7). Under a 100% irrigation regime at field capacity, the addition of KH_2PO_4 led to a slight increase in fruit production from the lowest dose of 0.5 g/L. In the presence of moderate water stress (75%), a decrease is observed, particularly marked with 0,5 g/L (T5 = 1.00). However, the dose of 1 g/L (T6) allows to maintain a number of fruits similar to the control. Under severe stress (50% irrigation), the addition of KH_2PO_4 did not compensate for the effects of water deficit, and fruit production was greatly reduced, not exceeding one fruit per plant for T8 and T9.

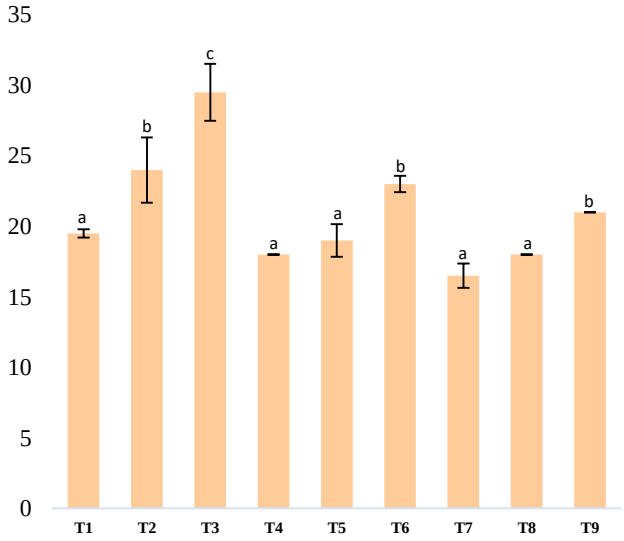

Figure 6. Effect of potassium phosphate (KH_2PO_4) on number of leaves in tomatoes grown under three irrigation regimes. 95% confidence interval for the average of 3 repetitions. The averages followed by different letters are significantly different ($p < 0.05$).

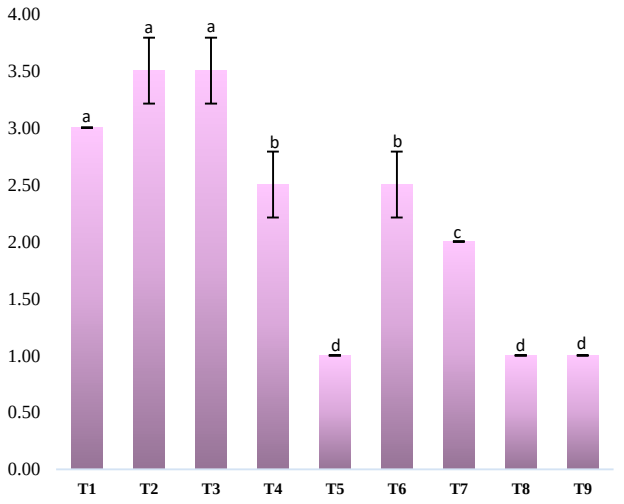

Figure 7. Effect of potassium phosphate (KH_2PO_4) on fruit count in tomatoes grown under three irrigation regimes. 95% confidence interval for the average of 3 repetitions. The averages followed by different letters are significantly different ($p < 0.05$).

***Length of the aerial and root parts*:** In comparison with the control plants, the length of the aerial part and that of the root

system of stressed plants decreased by -8.52% and -20.5% respectively in the presence of moderate stress and severe stress (Fig. 8). In stressed plants, the addition of KH_2PO_4, whatever its concentration, has no noticeable effect on the growth in length of these two types of organs. However, in the control plants, the application of KH_2PO_4 improved the stem length to the detriment of that of the root system, and this reduction increases with the concentration of KH_2PO_4. This result clearly shows that under normal irrigation conditions, KH_2PO_4 stimulated the multiplication of the apical meristematic cells of the stem but reduced those of the root apical meristems.

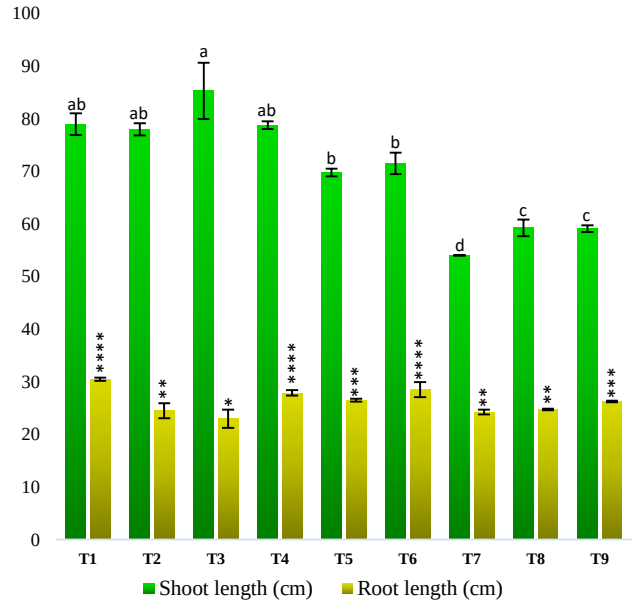

Figure 8. Effect of potassium phosphate (KH_2PO_4) on the length of the aerial part, and root (in cm) in tomatoes grown under three irrigation regimes. 95% confidence interval for the average of 3 repetitions. The averages followed by different letters are significantly different ($p < 0.05$). The averages with the same number of stars (*) do not differ significantly between them according to the Tukey test ($p < 0.05$).

Presentation of biochemical analysis results

***Chlorophyll content (a), (b), and carotenoids in the vegetative parts of tomato plants (µg/mg)*:** The application of water stress resulted in a decrease in chlorophyll (a), (b) and carotenoids in the leaves. But under these stressful conditions, the addition of KH_2PO_4 has allowed stressed plants to resume the synthesis of these photosynthetic pigments. In this connection, the best values for these three pigments were recorded respectively at the level of combinations: moderate stress X 1 g/L KH_2PO_4 and severe stress X 0.5 g/L KH_2PO_4 (Fig. 9). For the control plants, the contents of these pigments increased in the presence of the highest dose (1 g/L) and slightly decreased with the low dose (0.5 g/L) of KH_2PO_4.

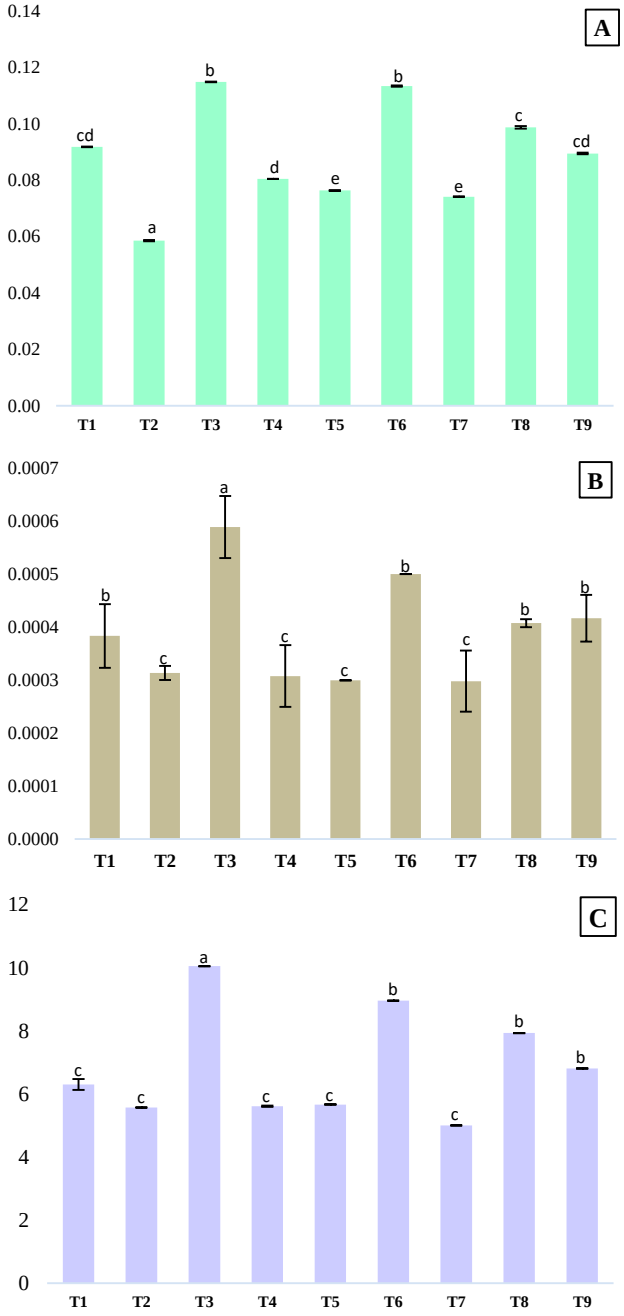

Figure 9. Effect of potassium phosphate (KH_2PO_4) on the content of photosynthetic pigments in the vegetative part of tomato plants grown under three irrigation regimes. (A) Chlorophyll a content (µg/mg MVF); (B) Chlorophyll b content (µg/mg MVF); (C) Carotenoid content (µg/mg MVF). 95% confidence interval for the average of 3 repetitions. The

averages followed by different letters are significantly different ($p < 0.05$).

***Proline content in mg/g DW in the vegetative part of tomato plants*:** By comparing the controls of the three irrigation regimes, increased water stress resulted in proline accumulation. But the levels of this amino acid decreased by -47% for both moderate stress treatments. However, in plants subjected to severe stress, levels dropped by - 11.76% and - 70.59% respectively when 0.5 and 1 g/L of KH_2PO_4 were added to the irrigation solution (Fig. 10).

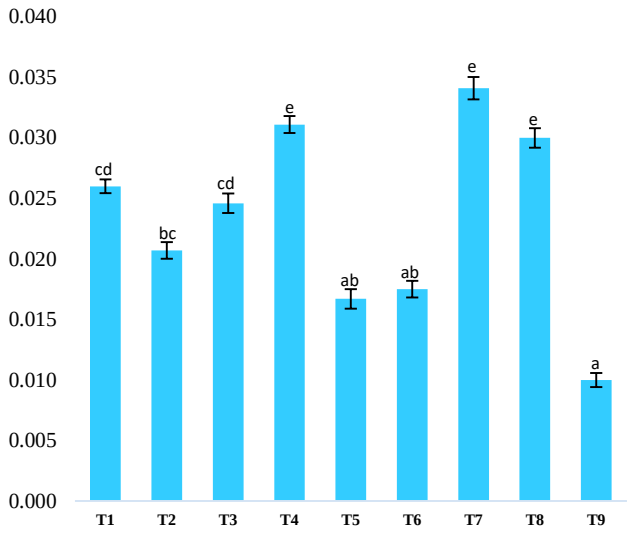

Figure 10. Effect of potassium phosphate (KH_2PO_4) on proline content (mg/g MF) in tomatoes grown under three irrigation regimes. 95% confidence interval for the average of 3 repetitions. The averages followed by different letters are significantly different ($p < 0.05$).

***Total sugar and soluble sugar content expressed as glucose content in the fruit portion of tomato plants*:** Glucose levels decreased compared to those of the control plants by - 39.14% and - 44.64% respectively in presence of moderate water stress (75% at field capacity) and severe (50% at field capacity). In the control plants, levels decreased at the lowest dose, with a significant reduction of - 56.47% with 1 g KH_2PO_4. On the other hand, in stressed plants, the levels of glucose fell, compared to each water stress control, only in the presence of 1g of KH_2PO_4. In the latter case, decreases are more pronounced with severe water stress (50% to field capacity) (Fig. 11, A).

In general, variations in total sugar levels from different treatments were similar to those of glucose, with reductions of about - 60% in plants grown under a severe water regime compared to the non-stressed control. Also, the results obtained show that the addition of KH_2PO_4 has no improving effect on sugar synthesis (Fig11, B).

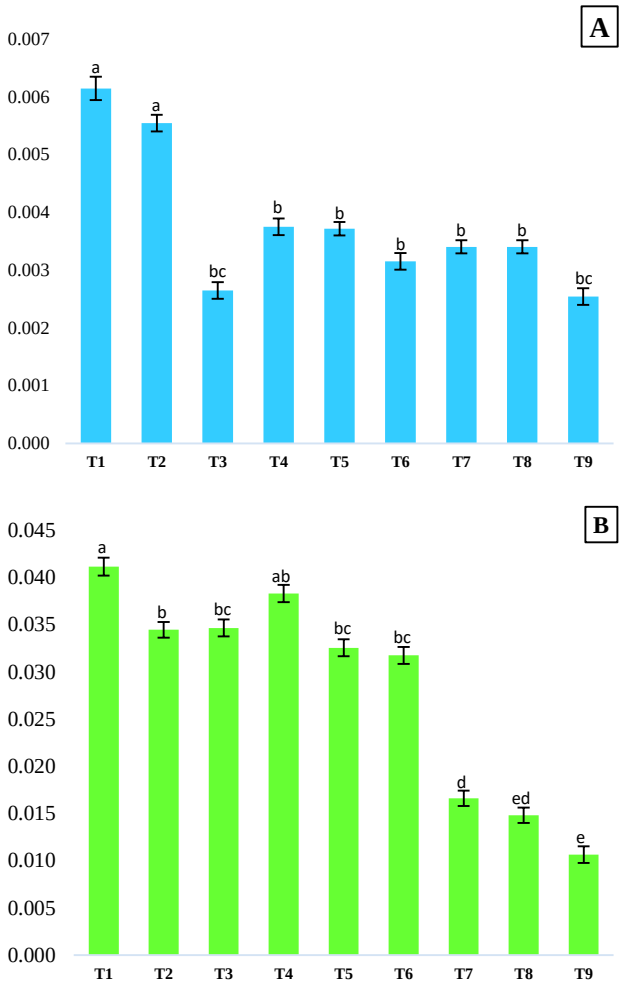

Figure 11. Effect of potassium phosphate (KH_2PO_4) on glucose and total sugars in tomatoes grown under three irrigation regimes. (A): Glucose content (mg/ml); (B): Total sugar content (mg/ml). 95% confidence interval for the average of 3 repetitions. The averages followed by different letters are significantly different ($p < 0.05$).

DISCUSSION

Under natural conditions, crop production is generally limited by water stress (Toure et al., 2021; Boyer et al., 1982), essentially reducing the photosynthetic activity of stressed plants. However, the extent of its depressive effect depends on several factors, including its intensity, phenological stage and specific sensitivity of the stressed plant. Because each plant species has its own resistance mechanisms that allow it to maintain its production under a given water stress (Hamidou et al., 2005).

Our results confirm the sensitivity of tomatoes to water stress. By comparing only, the controls of the three irrigation regimes with respect to field capacity (100%, 75% and 50% control), all parameters measured showed a decrease that is proportional to the intensity of stress applied. This reduction is the result of an adaptation strategy implemented by the stressed plant to survive in these limiting water conditions. In this respect, the first response of the plant, in the presence of a water deficit, is to reduce its transpiration by reducing the closure of its stomata (Damm, 2012). As a result, nutrient absorption and translocation in adequate amounts for proper growth to the upper parts will be reduced. Therefore, the tolerance of the plant to water deficit is related to its adaptive mechanisms, which give it a good absorption of ions and an increased synthesis of osmolytes necessary for the maintenance of osmotic adjustment and cellular integrity. Because cell turgor is required to maintain growth and development of the plant in adverse water conditions.

From the water content values recorded at the level of the aerial organs, potassium phosphate has improved only the water supply of stressed plants, without any stimulating effect on the production of aerial biomass.

On the other hand, at the root system level, the improvement of water supply induced by potassium phosphate was associated with an increase in the production of root biomass both in the control plants and in those subjected to moderate water stress. However, this synergistic effect between turgescence and cell multiplication was interrupted in the presence of severe water stress (50%). This result can be explained by a diversion of ATP for the synthesis of osmolytes essential to the survival of the plant at the expense of its cell multiplication. Thus, the direct involvement of KH_2PO_4 in improving the water stress tolerance of plants is proved by ensuring adequate at their photosynthetic organ (Adams et al., 1984). Similarly, it appears that the low concentration of KH_2PO_4 (0.5 g/L), is more favorable to root growth, in width and depth to increase the absorption area, regardless of the stress applied. This result is similar to that of Aslam et al. (2014), who worked on maize. This improvement in root growth was explained by the maintenance of sufficient K concentrations through negative regulation of the K channel involved in its transport from roots to xylems (Pilot et al., 2003), thus promoting their growth despite the stress conditions (Sharp et al., 1990). Therefore, adequate K cell concentrations are essential for plants to respond properly to various types of stress, such as drought (Zhang et al., 2016). The improvements obtained under water stress by adding KH_2PO_4 in this work are similar to those reported by Mpika et al. (2015), who worked on two tomato varieties: locale and Mongal.

It seems that this positive effect of KH_2PO_4 is attributed to its essential role in many physiological functions (Leigh et al., 1984; Shabala et al., 2010). In the same vein, numerous researches have demonstrated its involvement in the regulation of cell growth and wood formation (Trouy, 2015), in the water status of organs and the circulation of sap in xylem-systemsphloem, in nutrient and metabolite transport, as well as in stress responses (Trouy et al., 2015; Marschner et al., 2012; Demidchik, et al., 2014). It is also involved in the activation of a large number of plant enzymes linked to fundamental metabolic processes, such as glycolysis and the Krebs cycle (Sardans et al., 2021). Similarly, its movement through cell membranes or organelles can determine the final plant response (Zhang et al., 2016; Zhu et al., 2016). In the same sense, there are several common mechanisms influenced by water and potassium, such as photosynthesis, cell growth, stomatic conductance... (Hsiao et al., 1976; Nakro et al., 2020). Its positive effect on photosynthesis was justified by its association with high levels of chlorophyllin pigments (Babicz 2002; Hamano et al., 2002; Yagmur et al., 2004; Nakro et al. 2020). These results are in agreement with those of our work, which showed that high levels of these pigments were recorded with 1 g/L of potassium phosphate in the control plants. However, the best values of all three pigments were measured with 0.5 and 1 g/L KH_2PO_4 respectively under moderate and severe stress.

Our result highlighted the attenuating role of potassium phosphate on the adverse effects of water deficit on photosynthesis.

Our results are relative to those obtained by Son et al. (2011), which confirm that water deficit can control vegetative growth by reducing the vigor of the plant. This reduction was greater for the lowest water diets. Regardless of the stage of development in which water stress was applied, it resulted in reduced plant growth.

The application of potassium plays an essential role in plant growth (Mpika et al., 2015). This mineral element is said to stimulate photosynthesis in tomatoes and promote the transport of photosynthesized products in leaves to other parts of the plant (Header et al., 1971; Haeder et al., 1972). This explains the results we obtained from fresh and dry peas of the vegetative part (stem and leaf). Treatment at 0.5 g/L of KH_2PO_4 and 100% irrigation provide the best conditions to maximize vegetative growth.

Our yield results are similar to those of Mpika et al. (2015), who showed that high potassium intakes have no effect on the yields of three varieties of tomatoes grown under water stress. In the same vein, Rhue et al. (1986) have shown that excessive potassium intakes have only a limited or no effect on potato yield, improving only its tolerance to water stress. Similarly, Adams (1986) reported that an excess of potassium can lead to magnesium deficiency by reducing the number of flowers in tomato plants (Armengaud et al., 2004; Egilla et al., 2001). For glucose and total sugars, their contents decreased according to the intensity of the applied water stress, without any effect associated with the addition of KH_2PO_4. According to Martineau et al. (2018), this decrease in photosynthesis products under water stress is mainly attributed to the

reduction in the number of leaves and their surface area, and also to the acceleration of their winding and senescence. It may also be due to their use in the synthesis of other osmolytes involved in tolerance to this type of stress such as amino acids, organic acids and amides (Wang et al., 2010). In our work, the great part of the reduction of the contents of glucose and total sugars can be explained by the second hypothesis above. Because the content of proline, which acts as a protective osmolyte against metabolic and physiological stresses, increased under both water stress studied (Cuin et al., 2018; Zain et al., 2014; Teixeira et al., 2007). However, with 0.5 g/L of KH_2PO_4, the proline content is slightly higher in plants grown under a severe water regime compared to control plants. This result confirms the osmoregulatory role of proline, improving plants' tolerance to water stress. Thus, proline, along with soluble and total sugars, is involved exclusively in root osmoregulation, whereas potassium contributes to the osmotic adjustment of the leaves. However, an in-depth study will be necessary to explain the maintenance of root growth compared to that of the aerial part, despite its hydration (Fournier et al., 2005).

***Conclusion*:** This study highlighted the significant influence of the combination of water stress intensity and potassium phosphate (KH_2PO_4) concentrations on the growth, development and physiological responses of tomato plants grown under an agro-photovoltaic greenhouse.

The results obtained confirm that potassium phosphate contributes to improving water uptake efficiency in the tomato variety by ensuring good cellular turgor in the aerial parts and promoting proper root system development. This beneficial effect can be attributed to its role in maintaining leaf turgor and, potentially, to its involvement in the translocation of proline and sugars toward the roots. Several studies have confirmed the osmoregulatory role of proline and sugars under water stress conditions. Consequently, their observed decreases in the aerial parts can only be explained by their translocation to the roots. Based on this finding, we can infer that proline functions as an osmoregulator at the root cell level, while sugars provide the energy required for root growth.

Despite these promising results, it would be highly relevant to further investigate the mechanisms triggered by potassium phosphate fertilization in tomato plants by determining the specific contribution of each of its ions (K^+ and PO_4^{3-}) to drought tolerance.

Finally, our results deserve to be disseminated to farmers, particularly in arid and semi-arid regions, to improve the quality and yield of their crops. Indeed, fertilization with potassium phosphate may represent an effective strategy to enhance tomato plant tolerance to water deficit conditions—at a concentration of 0.5 g/L under severe stress, and 1 g/L under moderate stress.

***Acknowledgments*:** This work was supported by the Research Institute in Solar Energy and New Energies (IRESEN) in Morocco, within the project “CR-SEAPI”.

***CRediT author statement*:** Widad MOUSSA: Main author, experimental study execution. Noureddine AMENZOU and Said BOUGHRIBIL: Validation and revision of the experimental methodology. Aziz BENAMED: Project coordinator, setup of equipment, and supervision of experimental work.

***Conflict of interest*:** The authors declare that they have no conflict of interest.

***Funding*:** This work was supported by the Research Institute in Solar Energy and New Energies (IRESEN) in Morocco, within the project “CR-SEAPI”.

***Ethical statement*:** N/A

***Availability of data and material*:** The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

***Consent for publication*:** All authors consented to publish this research in JGIAS.

***SDGs addressed*:** Zero Hunger, Clean Water and Sanitation, Climate Action, Life on Land

***Policy referred*:** National Water Management Policies; Sustainable Agriculture and Food Security Policies.

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